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CERTAIN MECHANICAL STRENGTH PROPERTIES OF ALUMINUM ALLOYS 25S-T AND X76S-T

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SUMMARY

Tests have been made to determine certain mechanical strength properties of 25S-T aluminum alloy. Results are presented from static tests in tension and torsion, bending fatigue tests employing three different types of testing machines, and from impact tests of notched and unnotched specimens in tension as well as from Charpy impact tests made at several low temperatures. Information is included on the effects produced by repeated understressing and by anodizing, and a comparison is made of the strength properties of 25S-T alloy with data previously reported for the X76S-T alloy. (See reference 1.)

The results indicate that:

(a) The fatigue strength or maximum alternating stress that could be endured for a given number of cycles by notched specimens of these alloys decreased markedly as the mean stress in the cycle was increased in tension.

(b) The fatigue strength of notched 25S-T specimens was greater than that of the X76S-T specimens when the mean stress was a tensile stress.

(c) The fatigue strength of both alloys was greatly decreased by the presence of a notch in the specimens.

(d) A large number of cycles of understress produced no great or consistent change in the final fatigue strength of these two alloys.

(e) Anodizing produced a slight increase in fatigue strength of X76S-T alloy, but did not affect the endurance limit of the 25S-T alloy.

INTRODUCTION

The principal stresses developed in an airplane propeller blade in service arise from two causes, namely:

(a) A steady stress due to the centrifugal loading developed when rotating

(b) Alternating stresses produced by flexural vibrations of the blade

For a typical aluminum blade these steady stresses may be as much as 12,000 pounds per square inch and superimposed alternating stresses have been found as high as 20,000 pounds per square inch.

The face side of the blade is frequently scratched or nicked in service, producing notches that act as "stress raisers." These notches in the polished surface are the points from which fatigue failures of the blade may develop. Hence for design purposes it is necessary to know what maximum alternating stresses may be superimposed on either tensile or compressive mean stresses of various magnitudes without causing failure of the notched member. It is also very desirable to know what influence the repetition of a large number of cycles of understress (stress below the endurance limit) will have in raising or lowering the endurance limit of the metal in a propeller blade. This information is of importance in determining whether the service stresses normally encountered in flight would eventually damage the material, and in interpreting the results of laboratory tests of full size blades in which the vibratory stressses are increased by small increments after definite time intervals until failure occurs.

The main purpose of the investigation herein reported was to determine the flexural fatigue strengths of notched specimens of an aluminum alloy, designated as 25S-T, when subjected to six different ranges of stress, and to compare these values with the fatigue strengths of polished (unnotched) specimens without abrupt change in section. To give rather complete information on the mechanical properties of this metal which is commonly used for propeller blades, tests were also made to obtain values of the static and impact properties.

A second purpose of the investigation was to determine whether the endurance limit of the metal was appreciably affected by a large number of cycles of understressing or by anodizing the surface. The data contained in this report are the results of a continuation of the series of tests reported in reference 1 on X76S-T alloy. The results of further tests of the X76S-T alloy are also given in this report.

The tests reported herein were conducted at the Engineering Experiment Station, University of Illinois, under the sponsorship of the National Advisory Committee for Aeronautics. The Hamilton Standard Propellers Division of the United Aircraft Corporation cooperated in the investigation and provided machined specimens for a number of these tests.

Acknowledgment is made to Mr. O. C. Worley, Mr. G. D. Chambliss, and Mr. R. L. Brown, Jr. for their assistance in conducting the research.

MATERIAL AND METHODS OF TESTING

Types of test.- Three types of test were made on 25S-T aluminum alloy to determine the ordinary mechanical properties of the material as well as the fatigue of strengths. These tests may be outlined as follows:

(1) Static tests were made of notched and unnotched tensile specimens and of unnotched torsion specimens to determine the strength, stiffness and ductility of the metal. The term "unnotched" will be used throughout this report to designate specimens without an abrupt change of section in the portion under test.

(2) Impact tests were made of notched and unnotched tensile specimens, and of standard notched Charpy bending impact specimens, at ordinary room temperatures and at low temperatures, to give some indication of the energy absorbing capacity and of the relative notch sensitivity of the material under suddenly applied loads.

(3) Repeated load (fatigue) tests were made in three types of testing machine, namely:

(a) High-speed rotating cantilever beam fatigue machines using (small) 0.40-inch diameter round specimens

(b) Krouse rotating cantilever beam fatigue machines using specimens 0.26-inch in diameter

(c) Krouse flat plate fatigue machines which subjected rectangular specimens to a vibratory bending action without rotating the test piece.

Both notched and unnotched specimens were tested in the vibratory bending and the Krouse cantilever-beam fatigue machines; whereas the high-speed rotating beam machines have been used only to determine the endurance limits of polished unnotched specimens.

Material and test specimens.- Most of the tests herein reported were made on the aluminum alloy that is designated and sold under the commercial code number 25S-T. The chemical composition of this alloy was as follows:

	Percent
Copper	4.28
Iron	.36
Manganese	.77
Silicon	.76
Aluminum	Balance

All specimens tested were from the same heat of metal that was hot rolled from a 12- by 12-inch ingot, to round bars 1 inch in diameter. The bars were then given a solution and precipitation hardening heat treatment by holding for 10 hours at 960° F quenching in cold water, and aging for 10 hours at 340° F.

Several additional tests on X76S-T alloy were also made to study the effects of anodizing and of repeated understressing. The detailed chemical composition and heat treatment of the X76S-T alloy were as follows:

	Percent
Copper	0.6
Zinc	7.6
Magnesium	1.6
Manganese	.5
Titanium	.1
Iron	.5
Silicon	.25
Aluminum	Balance

All specimens tested were from the same heat of metal that was reduced, by the latest methods of processing, to bars 1 inch square which were subsequently swaged in a pair of swaging dies to 1 inch diameter round. The bars were then given a solution and precipitation hardening heat treatment by holding for 10 hours at 860° F, quenching in water, and aging for 12 hours at 275° F.

The details of the specimens used for the ordinary static tensile tests to determine the physical properties of the unnotched specimens are shown in figure 1a, and the type of notched specimen used in the static tensile test is shown in figure 1b. Three specimens of each of these two types were tested in an Amsler Hydraulic Universal Testing Machine having a capacity of 50,000 pounds. Additional tests were also made on tensile specimens having the same nominal diameter as that in figure 1a, but having an over-all length of about $11\frac{1}{2}$ inches so that an 8-inch gage length could be employed.

In figure 1c is shown the type of specimen used to determine the static torsional properties of the material. The tensile impact specimen shown in figure 2a was polished with No. 00 emergy paper and the diameter of the specimen near the center was reduced about 0.003 inch less than at the ends of the 2-inch gage lengths.

The notched tensile impact specimen shown in figure 2b contained a notch machined with a carefully ground tool

that was checked for accuracy of shape by examining in a metallurgical microscope at 100X. This notched impact specimen was geometrically similar to that of the notched static tensile specimen in figure 1b. The notched bending specimen used was the standard Charpy impact specimen of the dimensions shown in figure 2c.

The types of specimen used in the rotating-beam fatigue machines are shown in figure 3 and those tested in the vibratory bending fatigue machines are shown in figure 4. Those specimens without abrupt change of section (3a, 3b, and 4a) were all polished longitudinally with No. 00 emery paper and oil to remove tool marks and circumferential scratches before testing. All of these specimens were polished by one man to assure uniformity in the polishing operations. The notched specimens (3c and 4b) were cut with carefully ground tools to assure uniformity in depth, angle of the V-notch, and radius at the root of the notch, on all specimens tested. Three faces of the notched specimen in figure 4b were polished longitudinally; the root of the notch, and the face containing the notch were left in the original machined condition.

The nominal stress in all fatigue specimens was calculated by using the ordinary flexure formula, $s = Mc/I$, in which s is the flexural unit stress (lb/sq in.) M is the bending moment at the critical test section (in.-lb), c is half the depth of the specimen (in.), and I is the moment of inertia of the net cross-sectional area (in.^{4}). For those specimens containing notches the values of stress given in this report are those at the root of the notch computed by the above formula using the values of c and I for the minimum cross-sectional area.

The tests of rotating-beam fatigue specimens were made in two Krouse, 120 inch-pound capacity, cantilever machines of the type shown in figure 5, which were operated at 6000 rpm. Also employed were four small high-speed cantilever beam machines of the type shown in figure 6 that were run at 10,000 rpm. The vibratory bending fatigue tests were made in six Krouse Flat Plate Fatigue machines of the type shown in figure 7, which were run at 1750 rpm.

RESULTS OF TESTS

Static tests.- Lower portions of the tensile stress-strain curves for three unnotched specimens of 25S-T alloy are shown in figure 8 and a typical complete stress-strain diagram for one of these is shown in figure 9. The results

of these three static tensile tests on a 2-inch gage length and of three additional tests on a 8-inch gage length are tabulated in table I. The tensile tests were carried out in accordance with A.S.T.M. Standard Methods for Testing Metallic Materials, designation E8-36.

For purposes of comparison with the 25S-T alloy the average properties of X76S-T alloy as obtained in the previously reported series of tests have been added to each of the tables giving the results of static or impact tests. It will be noted in table I that the 25S-T alloy had lower static tensile strengths, but slightly higher ductility and modulus of elasticity than the X76S-T alloy.

The Brinell hardness, using 500-kilogram and 10-millimeter ball of the 25S-T alloy ranged from 102 to 118 in the various specimens tested and averaged about 111. The X76S-T alloy had a higher average hardness, 146 Brinell, than the other precipitation hardening aluminum alloys.

The greater portions of the tensile stress strain curves on <u>notched</u> specimens are shown in figure 10, and the results of these three individual tests are summarized in table II along with the corresponding values for X76S-T alloy. The relative ratios of strengths shown in this table for each metal are of approximately the same magnitudes except for the very high ratio of yield strength to ultimate strength exhibited by the X76S-T alloy. The introduction of a notch in the static tensile specimens of X76S-T alloy also caused a much greater proportionate loss in percent elongation than did the same notch in specimens of 25S-T.

Static torsion tests were made of three solid specimens of the type shown in figure 1c. The lower portions of the torque-twist curves for these tests are shown in figure 11. A summary of the data obtained from these three tests along with similar data for X76S-T alloy is shown in table III. Here again the yield strength for X76S-T alloy was a much higher proportion of the ultimate strength, as represented by modulus of rupture than for the 25S-T alloy. However, by comparing tables I and III it will be noted that the modulus of rupture of 25S-T in torsion was a greater proportion of its static tensile strength than was the case for the X76S-T.

<u>Impact tests</u>.- The tensile impact tests were made in a standard Charpy machine having a capacity of 223 foot-pounds equipped with special auxiliary specimen grips containing spherical seats that were designed to minimize bending or eccentric loading on the specimen

during test. Tensile impact tests were made both at room temperature (+80° F) and at a low temperature (−40° F) since it was felt that any change in properties of the metal that would be induced by low temperatures would be of importance.

Cooling of the specimen to the low temperature was accomplished by immersing the pendulum, test specimen, and attached holders in a bath of acetone contained in a special insulated box. The entire bath was cooled by adding dry ice until the desired temperature was obtained and the bath was then maintained at this temperature for at least five minutes before testing the specimen. Previous calibration tests in which readings were taken on several thermocouples attached to a specimen indicated that this was a sufficient interval of time for these small specimens to reach a uniform temperature equal to that of the bath. In performing the actual test of the specimen only about 4 seconds elapsed between the removal of the box containing the coolant and the actual fracturing of the specimen; hence it was felt that the temperature of the specimen did not change appreciably previous to testing since it was surrounded by relatively heavy masses of metal cooled to the same temperature as the bath.

The test data showing the energy required to rupture each specimen tested and the average values obtained for each group of specimens are shown in table IV for the tests at +80° F, and in table V for the tests at −40° F. For purposes of comparison one may regard the energy required to rupture the unnotched specimens (column 3) as indicative of the impact strength, and the percentage of elongation and reduction of area (columns 6 and 9) as measures of the ductility of the material under these conditions of testing. A ratio of the values obtained for notched specimens to those for unnotched specimens given in columns 5 and 8 gives a rough measure of the notch sensitivity of the metal under rapid loading.

For a rough comparison with the values of 25S-T alloy listed in tables IV and V there is included a new set of data for X76S-T alloy tested under the same conditions. (The previously reported tensile impact tests of unnotched specimens of X76S-T alloy were made on specimens 0.25 inch diameter instead of 0.20 inch diameter, as in the present tests.) (See reference 1.) It may be seen that the 25S-T alloy specimens required more

energy to rupture than those of the X76S-T alloy. The ratio of energy absorbed by the notched specimens to that for the unnotched specimens was also greater for the 25S-T alloy indicating that this metal was somewhat less sensitive to the damaging effects of a notch than was the X76S-T alloy.

The average energy absorbed by all specimens of 25S-T tested at +80° F (see columns 3 and 4 of table IV) was below that for the specimens tested at -40° F; however, the X76S-T alloy showed no appreciable change in energy absorbing properties over this range of temperatures. A comparison of the average values listed in tables IV and V therefore leads to the conclusion that the 25S-T exhibited practically the same ductility and notch sensitivity and slightly greater energy absorbing capacity in the tensile impact tests at -40° F as it did at room temperature.

The results of a series of notched bar Charpy <u>bending</u> tests at temperatures ranging from +70° F to -70° F are shown in table VI. The Charpy specimens of 25S-T alloy exhibited practically the same energy absorbing capacity at -40° F as at room temperature. However, there was a pronounced drop in energy absorption by the 25S-T specimens when the temperature was dropped to -70° F.

A comparative picture of the results of some of the above impact tests is shown in figure 12. Perhaps the most interesting feature shown in table VI and figure 12 is the fact that the 25S-T specimens absorbed from three to four times as much energy as the X76S-T alloy in the Charpy bending impact tests. Even though the X76S-T had a much greater tensile strength than 25S-T it therefore exhibited a much lower strength for a service condition in which a notched member would be required to withstand a relatively rapid or impact loading. Figure 12 also indicates that all of the average tensile impact properties of 25S-T were slightly superior to those of X76S-T.

<u>Repeated load tests for completely reversed bending</u>.- The results of the rotating-beam fatigue tests of unnotched specimens of 25S-T alloy are shown in the S-N curves of figures 13 and 14. These figures include data from two different types of testing machine operated at different speeds. Figure 15 shows the results of tests of rectangular

specimens of 25S-T in the vibratory bending fatigue machine, which tests were made at the rate of 1750 cycles per minute. The endurance limits of these groups of unnotched polished specimens have been scaled as the ordinates to the S-N curves at 10 million, 100 million, and 500 million completely reversed cycles of stress and are listed in table VII. The endurance limits for the vibratory bending tests have not been carried out to 500 million cycles of stress because of the excessive time required to run these machines to such a large number of cycles; about seven months time would be required to run one specimen to 500 million cycles.

A comparison of the endurance limits listed in table VII for 100 million cycles of stress indicates that the differences in values obtained from the three types of testing machine were not great and that these differences are consistent with the variations commonly obtained from fatigue test results. Test results of several investigators have indicated that small specimens of a metal often exhibit a higher endurance limit than that obtained from tests of larger specimens. Also several groups of tests of rectangular vibratory bending specimens of steels, examples of which are presented in reference 2, results in slightly lower endurance limits as compared with those obtained for round specimens tested as rotating beams. It will be observed that the endurance limit of 18,000 pounds per square inch for the rectangular specimen, based upon 100 million cycles of stress, was only 1000 to 2500 pounds per square inch below the values obtained from the rotating beam tests.

In the previous report on X76S-T alloy it was found that the rectangular type specimen of this metal had an endurance limit of only 16,500 pounds per square inch; wheras the endurance limit of three types of round specimen varied from 22,000 to 24,000 pounds per square inch. No definite explanation for this great decrease in strength of the rectangular specimens of X76S-T alloy has been found. Three subsequent tests of X76S-T alloy were made with specimens that had the sharp projecting corners rounded and polished to 1/16-inch radius. One of these specimens tested at 22,000 pounds per square inch ran over 100 million cycles without fracture; whereas, the other two specimens tested at 25,000 and 26,000 pounds per square inch failed at only about 300,000 cycles which was slightly short of the normal S-N curve for the rest of the rectangular specimens. This scatter of data, together with

with that obtained in the original tests of the rectangular specimens of X76S-T, tends to indicate that there may have been mechanical defects such as inclusions or high residual stress present near the surface of the original bar stock. If such defects were present they would have a tendency to decrease the fatigue strength of the (larger) rectangular specimens more than they would in the case of the small round specimens.

In the lower portion of figure 13 is plotted the S-N curve for the rotating beam specimens of 25S-T with a V-notch. By scaling the ordinates at 100 million cycles of stress the values of the endurance limits were obtained as 19,000 pounds per square inch for the unnotched specimens, and about 10,000 pounds per square inch for the notched specimens. By using the ratio of these two endurance limits as a measure of the factor of stress concentration k caused by the notch, a value of $k = 1.9$ is found. However, if this calculation is based on the endurance limit at 500 million cycles of stress a value of $k = \frac{16,500}{10,000} = 1.65$ is found. These values indicate that the "notch sensitivity" of the 25S-T alloy was smaller than that of X76S-T for which alloy a value of $k = \frac{22,000}{9,000} = 2.44$ was obtained at 100 million cycles of stress under the same conditions.

In figure 15 is shown the S-N curve for the rectangular vibratory bending specimens of 25S-T with a V-notch tested under completely reversed cycles of stress. Here again the apparent stress concentration factor at 100 million cycles of stress was $k = \frac{18,000}{7,500} = 2.4$. This value is slightly higher than the value of $k = 2.2$ obtained under the same conditions for the X76S-T alloy. However, in this latter case it is felt that the reason for the lower value of k for the X76S-T alloy was due primarily to the abnormally low value of endurance limit that was obtained for the unnotched rectangular specimens. In fact, the <u>notched</u> rectangular specimens of 25S-T and of X76S-T had <u>exactly</u> the same endurance limit at 100 million cycles of stress even though the static tensile

strength and rotating beam endurance limits of polished specimens of X76S-T were greater than those of the 25S-T alloy. Moreover, the notched rotating beam specimens of 25S-T had a slightly higher endurance limit (10,000 lb/sq in.) than did those of the X76S-T alloy (9,000 lb/sq in.).

Further fatigue tests were made of rotating beam specimens treated by Hamilton Standard Propellers Company to study the effects of anodizing the surface of these two alloys. The results of these tests are shown in the S-N curves of figures 14 and 16. It will be observed that the S-N curve for the 25S-T alloy was practically unaffected by anodizing; whereas the data for the anodizing X76S-T in figure 16 showed considerable scatter but indicated a strengthening effect that raised the endurance limit about 3000 pounds per square inch to a value of 25,000 pounds per square inch at 500 million cycles of stress. Hence, it may be concluded that the surface effects produced by anodizing did not lower the fatigue strength below that of polished specimens, and may actually prove beneficial for some types of alloys.

Effects of range of stress on endurance limits of notched rectangular specimens.- To study the effect of range of stress on the endurance limit of specimens with a V-notch, tests were made in the vibratory bending machines with specimens subjected to a mean or steady stress on which was superimposed a completely reversed alternating stress. Six different endurance limits were determined corresponding to three different ranges in which the mean stress at the root of the notch was a tensile stress, two ranges in which the mean stress was compressive stress, and one range in which the mean stress was zero (completely reversed stress cycle).

The S-N curves for stress cycles in which the mean stress at the notch was a tensile stress are shown in figure 17, and the S-N curve for the completely reversed stress cycle is shown in the lower portion of figure 15. The endurance limits for these four stress cycles have been obtained by scaling the ordinates to the S-N curves at 100 million cycles of stress and these values are shown in table VIII for 25S-T.

For the two ranges in which the mean or steady stress at the notch was a compressive stress the specimens developed cracks at the root of the notch but did not completely fracture even though subjected to a large number

of cycles of superimposed alternating stress. Photographs of some of these cracks showing views looking down into the notch are presented in figure 18. The small dark areas in these figures are regions where small pieces of metal have cracked out and spalled off, but this spalling occurred only for specimens tested at relatively high stresses.

For specimens tested at lower stresses the cracks formed were very small and could not be seen without the aid of a low power microscope. Hence the fatigue test data could not be interpreted in the usual manner by plotting S-N diagrams based on <u>fracture</u> of the specimen and no definite indications of failure of a specimen were evident except for the microscopic cracking at the notch. Consequently it was decided to assume arbitrarily that cracks that could be seen with a 40X microscope constituted failure of a specimen. The endurance limits were thus obtained by plotting in figure 19 the approximate number of cycles at which the first cracks were visible with the low power microscope. The values of endurance limit for 25S-T determined in this manner for the two compressive stress cycles are listed in table VIII.

The effect of the range of stress on the endurance limits of the V-notch specimens of 25S-T alloy is illustrated in the modified Goodman diagram of figure 20 on which are plotted the data of table VIII. On this diagram the ordinates represent the minimum stress (S_{min}) and the maximum stress (S_{max}) of the stress cycle and the abscissas represent the corresponding mean stress (algebraic average of S_{min} and S_{max}). For any given mean stress the algebraic difference between S_{max} and S_{min} represents the total range or double amplitude of the superimposed alternating stress that will cause failure after approximately 100 million cycles of stress.

It will be observed that as the algebraic value of the mean stress in the cycle was decreased from a large tensile (+) stress to zero and thence to a compressive (−) stress, an appreciable increase occurred in the total alternating range of stress required to cause failure. This is shown more definitely by the curve in figure 21 in which the ordinates indicate the total alternating stress range ($S_{max}-S_{min}$), and the abscissas represent the

corresponding mean stress in each cycle. The data previously obtained in tests of M-68 are also plotted in figure 21 for direct comparison with the 25S-T alloy.

Considering these data and the fact that no fractures occurred in the specimens tested with compressive mean stresses at the notch, it is evident that both alloys can withstand considerably greater magnitudes of superimposed alternating stresses when the mean stress is decreased from a tensile to a compressive stress.

Effect of repeated understressing on the fatigue strength.- Two types of test were made in the rotating beam machines to determine the effect produced on the fatigue strength of these two aluminum alloys by repeated cycles of understressing or stresses below the endurance limit. These tests may be briefly outlined as follows:

(a) Tests in which a group of specimens were subjected to 100 million completely reversed cycles of a given stress below the normal S-N curve, and the endurance limit of the group of specimens then determined in the usual manner. This series of tests will be referred to as "prestress tests."

(b) Tests in which a specimen was started at a stress somewhat below the endurance limit and the magnitude of stress was increased by a small increment each time the specimen had been subjected to a definite number of completely reversed cycles of stress. The increments of both stress and number of cycles employed in the tests were varied somewhat, but in many cases the stress was increased by 2000 pounds per square inch each time the specimen had been subjected to 100 million cycles of stress. These tests of individual specimens will be referred to as the "step-up" tests.

The results of the prestress tests of 25S-T alloy are plotted in the S-N diagram of figure 22. The individual plotted points in this figure show the final stress and number of cycles for failure of a specimen after being originally prestressed at stresses of 15,000, 16,500, or 18,500 pounds per square inch. Also shown are the points obtained for tests of specimens without prestressing; that is the open circles show points that were previously plotted in the lower half of figure 14 to determine the normal S-N curve for 25S-T. The broken

curves outline the scatter band obtained in tests of the unprestressed metal, and it will be observed that practically all of the prestress test results fall within this band. Hence, it may be concluded that the prestressing employed (for 100 million cycles) had no effect on the fatigue strength of the 25S-T alloy.

Figure 23 shows the results of the prestress tests of X76S-T in a somewhat similar manner. In this case, however, the results are compared with the normal S-N curve for the X76S-T alloy as traced directly from the curve shown in the lower portion of figure 16 for the unprestressed metal. Since the scatter band for the untreated X76S-T was rather narrow, the data of figure 23 indicate that the fatigue strength of X76S-T was increased a small amount by the prestressing employed. The endurance limit at 500 million cycles of stress was apparently increased about 2000 pounds per square inch by prestressing at 20,000 pounds per square inch and was increased about 1000 pounds per square inch by prestressing at 21,000 pounds per square inch. These effects are rather small, but in general most of the specimens of X76S-T that were prestressed ran for a considerably greater number of cycles before fracture than would be indicated by the normal S-N curve for the unprestressed metal.

The results obtained from the step-up tests of individual specimens are shown in table IX for both the 25S-T and X76S-T alloys. As may be expected these results of fatigue tests of individual specimens showed considerable scatter in the number of cycles sustained by a specimen before fracture.

The data in table IX for the step-up tests of <u>unnotched</u> specimens of 25S-T alloy have been plotted in figure 24 along with the normal S-N curve for the metal (which was previously shown in fig. 14). The open circles at the lower ends of the vertical lines in figure 24 represent the magnitudes of stress at which each specimen was first started, and the increments of increase in stress (after each 100 million cycles) are shown by the bars crossing these vertical lines. The points plotted with solid symbols indicate the maximum stress before fracture and the number of cycles <u>at the maximum stress</u> required to produce fracture. The open symbols plotted on the right hand side represent the total <u>number</u> of cycles of stress resisted by the specimen during the entire test.

It will be observed that the total number of cycles of stress sustained by each 25S-T specimen in the step-up tests was much greater than had been obtained from tests of the normal metal when tested only at a constant stress having a magnitude equal to the maximum stress reached during the step-up tests. On the other hand the life of nearly every step-up specimen after the maximum stress had been reached was somewhat smaller than had been obtained for the normal S-N curve. The fact that five of the specimens failed at 20,000 pounds per square inch would indicate that the large number of cycles of previous understress had damaged these specimens a slight amount since the metal would normally have run a full 100 million cycles at this stress without fracture.

However, when the data in table IX for the step-up tests of the three <u>notched</u> specimens of 25S-T are compared with the S-N curve plotted for the unprestressed metal in the lower half of figure 13, it is found that these three specimens ran for about the same number of cycles (at the maximum stress) as the unprestressed specimens. Hence the fatigue properties of the notched specimens of 25S-T appeared to be unaffected by the understressing process.

As a result of all the step-up tests it was concluded that in general this type of understressing had no consistent effect in either raising or lowering the number of cycles which a specimen could withstand at the maximum stress before failure. By disregarding the previous stress history and plotting only the number of cycles at the maximum stress, the points usually fall within the scatter band for the unprestressed metal though there is a tendency for more scatter of results to be obtained by the step-up method of test.

DISCUSSION OF RESULTS

Perhaps the most important results of the tests are those showing the effects of range of stress on the endurance limits of notched specimens as presented in table VIII and in figure 21. When subjected to a service condition such as that in an airplane propeller, where the face of the blade is often scratched or notched by stones striking the blade, the fatigue strength of the metal in a notched condition is of primary importance. Moreover,

the stresses developed in a propeller blade vary over a rather wide range depending on the service condition.

In general, the results of the fatigue tests with notched specimens indicated that both alloys could withstand a greater alternating stress range without the formation of fatigue cracks when the mean stress in the cycle was changed from a tensile to a compressive stress. In addition, the fatigue cracks developed at the root of a notch did not spread rapidly when the mean stress was compressive, and no complete fractures of the specimens were obtained even when stresses somewhat above those required to produce cracking were repeated 100 million times. Thus if a notched member made of this metal were designed to operate with the mean stress at the notch a compressive stress, an additional factor of safety against complete fracture would exist; any fatigue cracking at the notch could probably be detected by periodic inspections long before the cracking had developed to a dangerous extent.

It is interesting to note that the X76S-T alloy was much stronger in static tension and had a higher flexural fatigue strength, as obtained from unnotched specimens, than the 25S-T aluminum alloy. However, the X76S-T alloy exhibited a fairly high notch sensitivity as indicated by the reduction of fatigue and impact strengths of notched specimens below those of the polished unnotched specimens. When the data previously obtained for notched X76S-T alloy specimens were compared with the values listed in table VIII, it was found that the alternating stress range which could be resisted without failure was exactly the same for both alloys if the mean stress in the range was either zero or a compressive stress. However, as shown in figure 21, the 25S-T alloy resisted a greater range of alternating stress than did the X76S-T alloy when the mean stress was increased in tension. Consequently, the 25S-T alloy should be able to resist slightly greater vibratory stresses in a notched propeller blade, where the mean stress is a tensile stress, than the X76S-T alloy, even though the latter alloy exhibited greater strength in the fatigue tests of <u>unnotched</u> specimens.

Another factor of interest was the change in shape of the S-N curves as the range of stress was varied. By comparing the S-N curves for the notched specimens in figure 15 with those in figures 17 and 19 it will be

observed that:

(a) For tests with a compressive mean stress the curves are very steep and are fairly straight.

(b) For completely reversed stress the trend of the curve is somewhat flatter and approaches a horizontal asymptote after a large number of cycles.

(c) As the mean stress was gradually increased in tension the curves became very flat and tended to reach a fairly definite horizontal asymptote at a relatively small number of cycles in somewhat similar manner to the typical S-N curves for steels.

Therefore it is felt that the endurance limits listed for the <u>notched</u> specimens and based on 100 million cycles of stress would not have been decreased appreciably if the tests had been continued to 500 million cycles of stress, even though the endurance limits scaled from the S-N curves of <u>unnotched</u> specimens of 25S-T did show a pronounced drop between 100 and 500 million cycles of completely reversed stress. This fact may also have direct application in helping to determine the useful life of aluminum alloys in service. Thus for notched members subjected to a tensile mean stress and subjected to vibratory stresses somewhat below the endurance limit as determined from a test run to a relatively small number of cycles, say 100 million, it would appear likely that such stresses could be repeated almost indefinitely without failure of the members.

A comparison of the endurance limits of the various unnotched specimens (see last column, table VII) indicates there was little or no effect of speed of testing within the range of speeds used in the tests. The differences in numerical values of the endurance limits may be accounted for by small differences in the behavior of the three types of testing machine, and by slight variations in different bars of the same metal.

The results of the prestressing and the step-up tests of these two aluminum alloys were not conclusive in indicating that either a strengthening or a weakening effect was produced by repeated cycles of stress below the endurance limits listed. The prestress tests of X76S-T did indicate that a slight strengthening effect was pro-

duced; whereas the step-up tests of 25S-T produced a slight decrease in life of unnotched specimens, and the other tests in general fell about in the normal range for unprestressed metal. Hence, the results may be accepted as evidence that no consistent or appreciable change in fatigue strength was produced in these alloys by repeated cycles of understress. However, the large number of cycles of stress developed in understressing each specimen during the step-up tests may have had a tendency to cause any microscopic defects present in a specimen to open up, and thus result in more scatter of the final test data.

The fact that the fatigue strength of the anodized specimens was as great, or slightly greater, than that of untreated specimens should make this method of surface treatment very useful for aluminum alloy members in use on naval aircraft since anodizing is also reported to have increased the resistance of aluminum alloys to pitting produced by salt water spray.

A photoelastic test was made to check the theoretical stress at the root of the notch in the rectangular vibratory bending specimen shown in figure 4b. This test was made on a scale model of bakelite three times the size of the prototype. As a result of the photoelastic stress analysis it was found that the theoretical stress over a small area at the root of the notch was approximately three times the nominal flexural stress calculated for this section.

The value of the stress concentration factor for the notch in the rectangular vibratory bending specimens was therefore 3.0 from the photoelastic analysis; whereas, a value of 2.40 was obtained from the fatigue tests of 25S-T subjected to completely reversed stress. These numerical values give an indication of the relative notch sensitivity of the metal to the damaging effects of a notch.

CONCLUSIONS

As a result of the data obtained in this series of tests the following conclusions were formulated regarding the mechanical strength properties of these two aluminum alloys:

1. The static elastic and ultimate strengths and Brinnell hardness of 25S-T alloy were somewhat lower than the corresponding values for X76S-T alloy.

2. The percentage elongation and reduction of area, and the modulus of elasticity of 25S-T, were slightly greater than the corresponding values for X76S-T.

3. The tensile yield strength at 0.05 percent offset of the X76S-T alloy was approximately 0.9 of its ultimate strength and was therefore exceptionally high as compared with the corresponding value of most ductile materials. The yield strength of 25S-T alloy was 0.6 of the ultimate.

4. Tension and bending impact tests at low temperatures indicated that the percentage elongation and reduction of area and the energy absorbed by these two metals were not materially affected by a large drop in the temperature of testing below room temperature. The 25S-T alloy exhibited greater ductility and energy absorbing capacity and a smaller notch sensitivity in these impact tests than did the X76S-T alloy.

5. In the tension impact tests of both metals, a V-notch with 0.01 inch radius at the root caused large decreases in elongation in 2 inches, and in the energy required for rupture.

6. Tests of polished specimens of 25S-T subjected to completely reversed stress cycles on three different types of testing machine and operating at speeds varying from 1750 to 10,000 rpm, gave endurance limits ranging from 18,000 to 20,500 pounds per square inch at 100 million cycles of stress. Hence there was no appreciable change in the endurance limit under these conditions as the speed of testing was varied from 1750 to 10,000 rpm.

7. The introduction of a V-notch in the test section decreased the fatigue strength of the 25S-T alloy for completely reversed cycles of stress to between 42 and 61 percent of the strength of unnotched specimens, depending somewhat on the shape of the member tested.

8. Considering a range of stress to be composed of a steady stress and a superimposed alternating stress, it was found that as the mean or steady stress at the notch

was decreased from a tensile (+) stress to a compressive (−) stress the total range of alternating stress that could be resisted by the notched specimens of 25S-T without causing failure gradually increased from a range of 12,000 pounds per square inch for a tensile mean stress of 16,000 to a range of 17,000 pounds per square inch for a compressive mean stress of 8500 pounds per square inch.

9. Tests of notched specimens in which the range of stress was varied indicated that for a given number of cycles the 25S-T alloy could resist a greater range of alternating stress than the X76S-T alloy when the mean stress in the cycle was a tensile stress. When the mean stress was a compressive stress there was practically no difference between the endurance limits of notched specimens of these two alloys.

10. Step-up and prestress tests of both 25S-T and X76S-T alloys indicated that the large number of cycles of understressing developed in the previous stress history of these alloys had no appreciable or consistent effect in either raising or lowering their endurance limits.

11. Anodizing the surface of specimens of these two alloys produced no change in fatigue strength of the 25S-T alloy, but produced a slight increase in the fatigue strength of the X76S-T alloy.

Engineering Experiment Station,
University of Illinois,
Urbana, Ill., June 8, 1943.

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1. Dolan, Thomas J.: Effects of Range of Stress and of Special Notches on Fatigue Properties of Aluminum Alloys Suitable for Airplane Propellers. T.N. No. 852, NACA, 1942.

2. Moore, H. F.: Report of the Research Committee on Fatigue of Metals. A.S.T.M. Proceedings, vol. 41, 1941, p. 133.

TABLE I

STATIC TENSILE TESTS OF 25S-T ALLOY

[1/2 in. diameter unnotched specimens in fig. 1a]

Specimen	Yield strength		Ultimate strength (lb/sq in.)	Elongation percent in 2 in.	Percent in 8 in.	Reduction of area percent	Modulus of elasticity 1000 lb /sq in.	Ratio of Yield strength (0.05 percent offset) to tensile strength
	0.05 percent offset (lb/sq in.)	0.2 percent offset (lb/sq in.)						
T_7	33,200	36,000	55,100	22.0	13.25	50.5	10,400	0.603
T_8	33,700	36,600	50,300	22.5	12.9	47.1	10,560	.670
T_9	34,400	37,400	57,000	26.0	14.5	48.7	10,740	.603
T_1	34,400	37,200	56,700	24.5	------	48.6	10,400	.607
T_2	34,100	37,100	56,200	26.0	------	46.8	10,840	.607
T_3	31,800	35,100	54,800	27.5	------	52.6	10,880	.580
Average	33,600	36,600	55,000	24.7	13.55	49.0	10,640	.611

Comparative values for X76S-T Alloy (reference 1, table I)

Specimen	0.05 percent offset (lb/sq in.)	0.2 percent offset (lb/sq in.)	Ultimate strength (lb/sq in.)	Elongation percent in 2 in.	Percent in 8 in.	Reduction of area percent	Modulus of elasticity 1000 lb /sq in.	Ratio
Average	64,200	67,200	72,500	19.2		40.6	9,690	0.887

TABLE II

STATIC TENSILE TESTS OF NOTCHED SPECIMENS OF 25S-T ALLOY

[Gage length 2 in. on 1/2-in diam. notched specimens shown in fig. 1b]

Specimen	N25T1	N25T2	N25T3	Average	Comparative values for X76S-T alloy
Yield strength, 0.05 percent offset (lb/sq in.)	47,600	47,300	46,300	47,100	85,100
Yield strength, 0.2 percent offset (lb/sq in.)	53,100	52,600	51,400	52,400	92,500
Ratio: $\frac{\text{yield strength at root of notch}}{\text{yield strength of unnotched specimen}}$ at 0.05 percent offset	1.425	1.42	1.39	1.41	1.31
Ratio: $\frac{\text{yield strength at root of notch}}{\text{yield strength of unnotched specimen}}$ at 0.2 percent offset	1.45	1.44	1.41	1.43	1.37
Ultimate strength (lb/sq in.)	70,300	70,700	69,300	70,100	96,700
Ratio: $\frac{\text{tensile strength of root of notch}}{\text{tensile strength of unnotched specimen}}$	1.25	1.26	1.24	1.25	1.33
Elongation, percent in 2 in.	3.50	4.00	4.50	4.00	1.83
Ratio: $\frac{\text{Elongation of notched specimen}}{\text{Elongation of unnotched specimen}}$	0.135	0.154	0.173	0.154	0.09
Ratio: $\frac{\text{yield strength (0.05 percent offset)}}{\text{tensile strength}}$ (notched specimens)	.677	.668	.668	.671	.880

TABLE III.– STATIC TORSION TESTS OF 25S–T ALLOY

[Gage length 2 in. on 0.56 in. diam. specimen shown in fig. 1c]

Specimen	S–6	S–10A	S–10B	Average	Values for alloy X76S–T
Yield strength, (lb/sq in.)					
0.05 percent offset	22,400	22,400	23,100	22,600	39,500
0.20 percent offset	25,800	26,000	26,100	26,000	———
Modulus of rupture (lb/sq in.)	52,800	52,300	52,800	52,600	63,600
Modulus of elasticity (1000 lb/sq in.)	4,090	4,190	4,020	4,100	4,060
Ratio:					
$\frac{\text{Yield strength (0.05\% offset)}}{\text{Modulus of rupture}}$	0.423	0.428	0.438	0.430	0.621

TABLE IV.- TENSION IMPACT TESTS AT +80° F

	Specimen		Energy to rupture (ft-lb)		Ratio of column 4 to column 3	Elongation in 2 in., percent		Ratio of column 7 to column 6	Reduction of area, percent
	Unnotched	Notched	Unnotched[1]	Notched[2]		Unnotched	Notched		Unnotched
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
25S-T Alloy	U42	N42	49.7	20.3		15.5	(3)		42.5
	U51	N52	37.6	22.7		13.0	5.0		46.0
	U53	N53	44.9	20.4		16.5	5.0		50.9
	U6A		40.6			15.0			50.4
	U6B		40.4			15.0			50.4
	Average		42.6	21.1	.496	15.0	5.0	.333	48.0
X76S-T Alloy	13A		42.0			9.0			41.8
	13B		28.0			7.0			41.6
	13C		42.4			10.5			41.5
	U16A		35.9			9.5			35.0
	U16B		37.6			9.0			39.0
	Average		37.2	8.9		9.0	1.8		39.8

[1]Unnotched specimens are those without abrupt change in section as shown in figure 2a.
[2]V-notch specimen as shown in figure 2b.
[3]Specimen broke at end of gage length.

TABLE V.- TENSION IMPACT TESTS AT -40° F

	Specimen		Energy to rupture (ft-lb)		Ratio of column 4 to column 3	Elongation in 2 in., percent		Ratio of column 7 to column 6	Reduction of Area, percent
	Unnotched	Notched	Unnotched[1]	Notched[2]		Unnotched	Notched		Unnotched
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
25S-T Alloy	U41	N41	49.9	24.6		17.0	6.0		45.9
	U43	N43	51.4	26.5		17.0	6.5		44.6
	U52	N51	47.2	24.4		16.5	5.5		50.5
	Average		49.1	25.1		16.8	6.0	.357	47.0
X76S-T Alloy	13D		41.2			9.5			39.5
	13E		33.6			7.5			41.0
	13F		36.8			9.0			39.5
	Average		37.2	8.2		8.7	1.8		40.0

[1]Unnotched specimens are those without abrupt change in section as shown in figure 2a.
[2]V-notch specimen as shown in figure 2b.

TABLE VI.- CHARPY BENDING IMPACT TESTS 25S-T ALLOY

[Using V-notch specimen shown in figure 2c]

Specimen	Test temp. (°F)	Energy absorbed, (ft-lb)	Comparative values for X76S-T alloy (ft-lb)
12A	70	63.3	
11A	70	22.1	
12B	70	38.2	
11H	70	28.3	
		Average = 38.0	9.1
11B	30	29.0	
12C	30	51.6	
11C	30	38.2	
		Average = 39.6	9.1
12D	-40	53.4	
11D	-40	35.8	
11E	-40	24.1	
12E	-40	33.5	
		Average = 36.7	12.3
11F	-70	18.8	
11G	-70	20.7	
12F	-70	27.6	8.8
		Average = 22.4	

TABLE VII.- ENDURANCE LIMITS OF UNNOTCHED SPECIMENS OF 25S-T ALLOY WITH COMPLETELY REVERSED STRESS CYCLE

Machine	Shape of specimen at test section	Depth of specimen at test section (in.)	Endurance Limits (lb/sq in.)		
			for 10^7 cycles	for 10^8 cycles	for 5×10^8 cycles
Rotating cantilever beam (see fig. 3a)	round	0.26	24,000	19,000	16,500
Rotating cantilever beam (see fig. 3b)	round	.14	27,000	20,500	17,500
Vibratory bending (see fig. 4a)	rectangular	.25	22,000	18,000	-------

TABLE VIII.- EFFECT OF RANGE OF STRESS ON ENDURANCE LIMITS OF NOTCHED SPECIMENS OF 25S-T ALLOY AT 100 MILLION CYCLES OF STRESS*

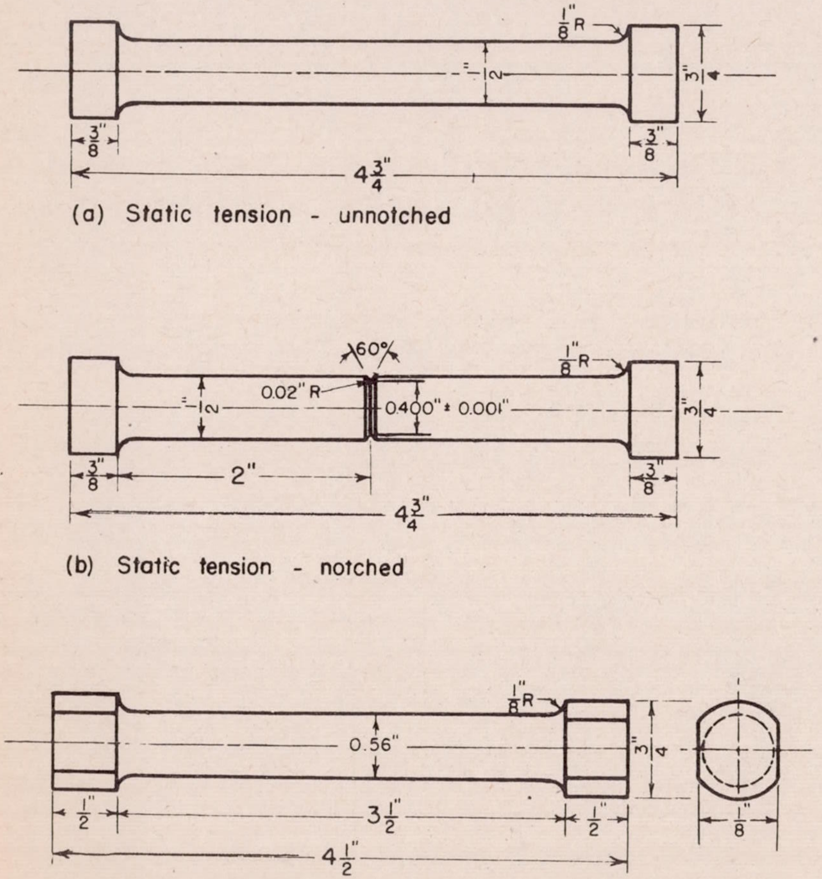
Type of stress variation	Maximum stress in cycle, (lb/sq in.) S_{max}	Minimum stress in cycle, (lb/sq in.) S_{min}	Mean stress in cycles (lb/sq in.)	Total alternating stress range (lb/sq in.) $S_{max}-S_{min}$
Zero to maximum in compression	0	-17,000	-8,500	17,000
+4,000 (lb/sq in.) to maximum in compression	+4,000	-12,000	-4,000	16,000
Completely reversed	+7,500	- 7,500	0	15,000
Zero to maximum in tension	+13,500	0	+6,750	13,500
+5,000 (lb/sq in.) to maximum in tension	+18,000	+5,000	+11,500	13,000
+10,000 (lb/sq in.) to maximum in tension	+22,000	+10,000	+16,000	12,000

*Plus stresses are tension; minus stresses are compression.

TABLE IX.- RESULTS OF STEP-UP TESTS

Specimen	Stress at start (lb/sq in.)	Increment of stress (lb/sq in.)	Cycles at each stress (millions)	Maximum stress before failure (lb/sq in.)	Cycles to fracture at maximum stress (millions)	Total of cycles run (millions)
25S-T alloy, unnotched 0.14 in. diam. specimens						
T6B	10,000	2000	100	22,000	72.8	684
12B	14,000	2000	100	20,000	94.0	405
T4B	15,000	2000	100	23,000	18.5	420
T5B	16,000	2000	100	20,000	92.0	292
T4D	16,000	2000	100	20,000	41.9	275
10D	16,000	1000	100	20,000	8.9	434
T6C	17,000	1000	100	20,000	48.8	360
25S-T alloy, notched 0.30 in. diam. specimens						
RN9	4,000	2000	100	12,000	1.4	409
RN11	5,000	2000	100	11,000	31.6	347
RN10	7,000	1000	100	14,000	0.9	733
X76S-T alloy, unnotched 0.14 in. diam. specimens						
E7B	18,000	2000	100	24,000	25.7	353
E7A	20,000	1000	100	26,000	24.7	648
R6A	21,000	1000	100	25,000	64.3	495
X76S-T alloy, notched 0.30 in. diam. specimens						
R68N11	8,000	1000	100	11,000	82.8	389
R68N9	8,000	1000	50	10,000	6.0	116
R68N8	4,000	1000	10	11,000	3.4	101

FIG. 1 SPECIMENS FOR STATIC TESTS

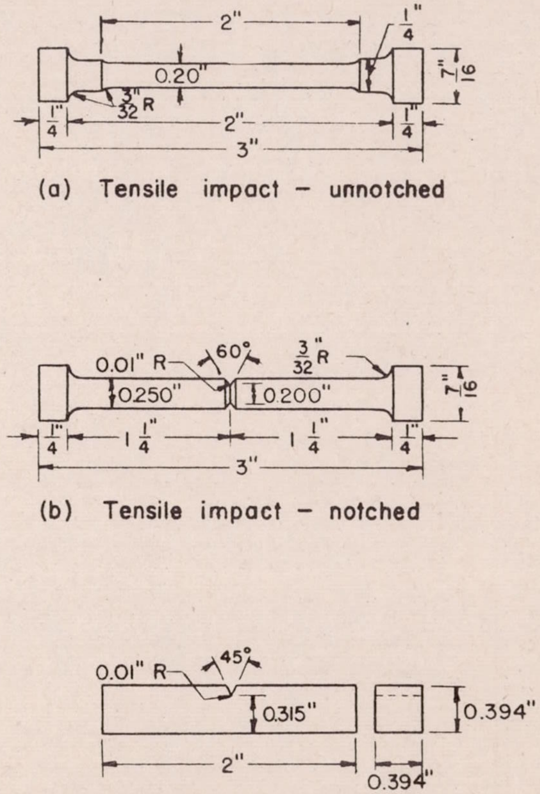


(a) Static tension - unnotched

(b) Static tension - notched

(c) Static torsion

FIG. 2 SPECIMENS FOR IMPACT TESTS

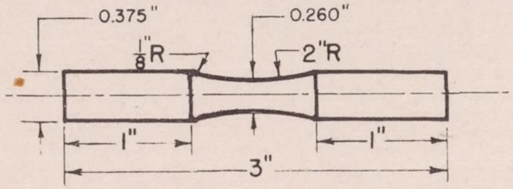


(a) Tensile impact – unnotched

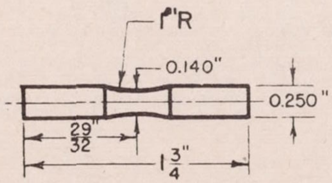
(b) Tensile impact – notched

(c) Charpy impact bending

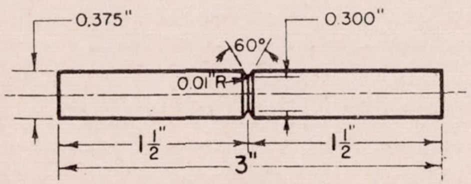
FIG. 3 SPECIMENS FOR ROTATING BEAM FATIGUE MACHINES



(a) Unnotched specimen

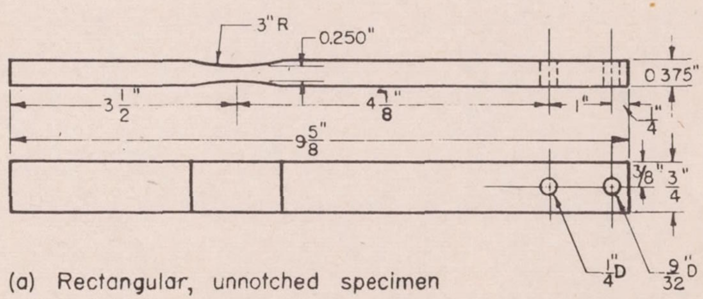


(b) Small, unnotched specimen

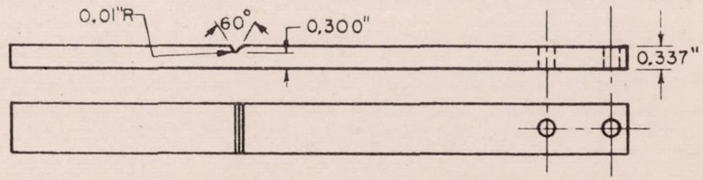


(c) Notched specimen

FIG. 4 SPECIMENS FOR FLEXURE FATIGUE MACHINES



(a) Rectangular, unnotched specimen



(b) Rectangular, notched specimen

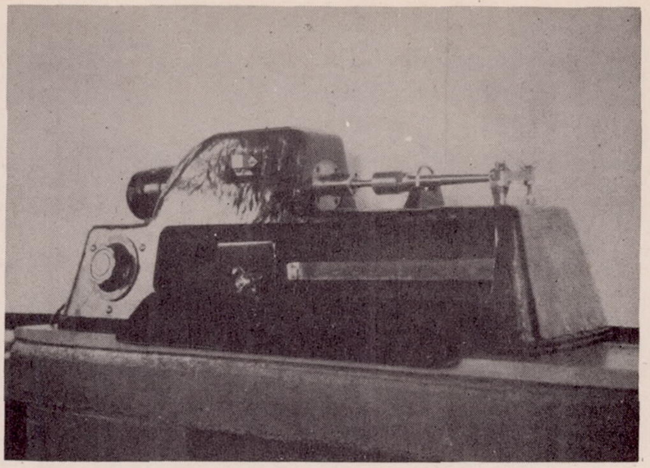


Figure 5.– Krouse rotating beam fatigue testing machine.

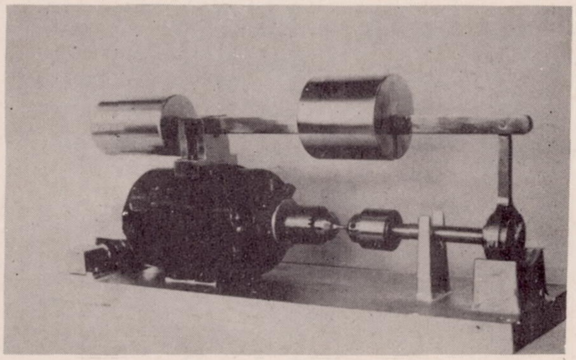


Figure 6.– Small high speed fatigue testing machine.

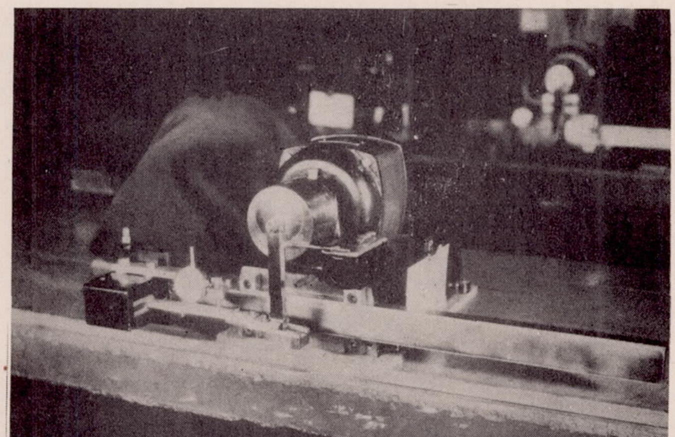


Figure 7.– Krouse flat plate fatigue testing machine.

FIG. 8

STATIC TENSILE TESTS — 25S-T ALLOY

LOWER PORTIONS OF STRESS-STRAIN DIAGRAMS

SPECIMENS; 8 IN. GAGE LENGTH; 1/2 IN. DIAMETER; UNNOTCHED

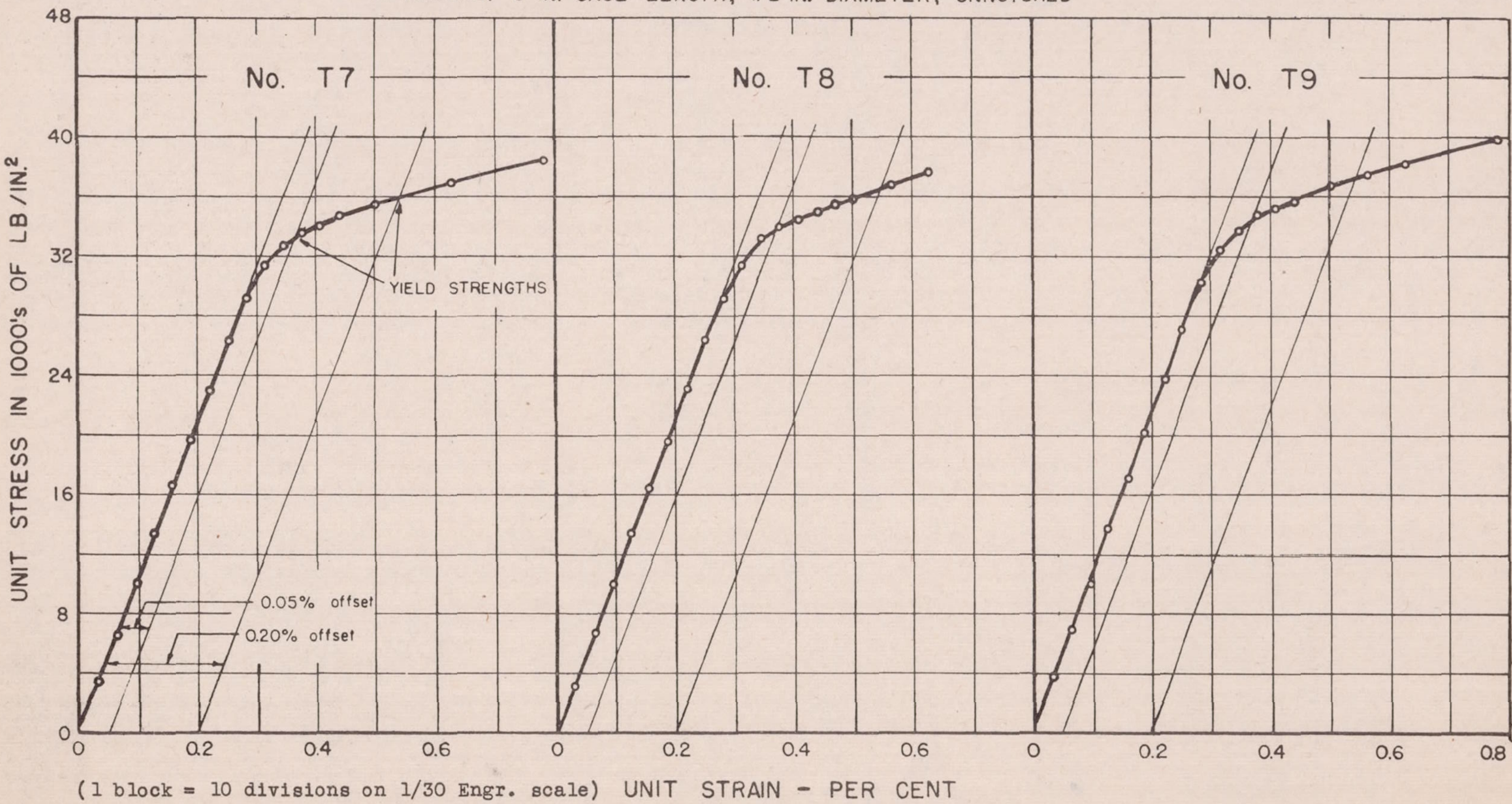


FIG. 9 STATIC TENSILE TEST—25 ST ALLOY

SPECIMEN NO. 25—T1

2 IN. GAGE LENGTH .5035 IN. DIAM.

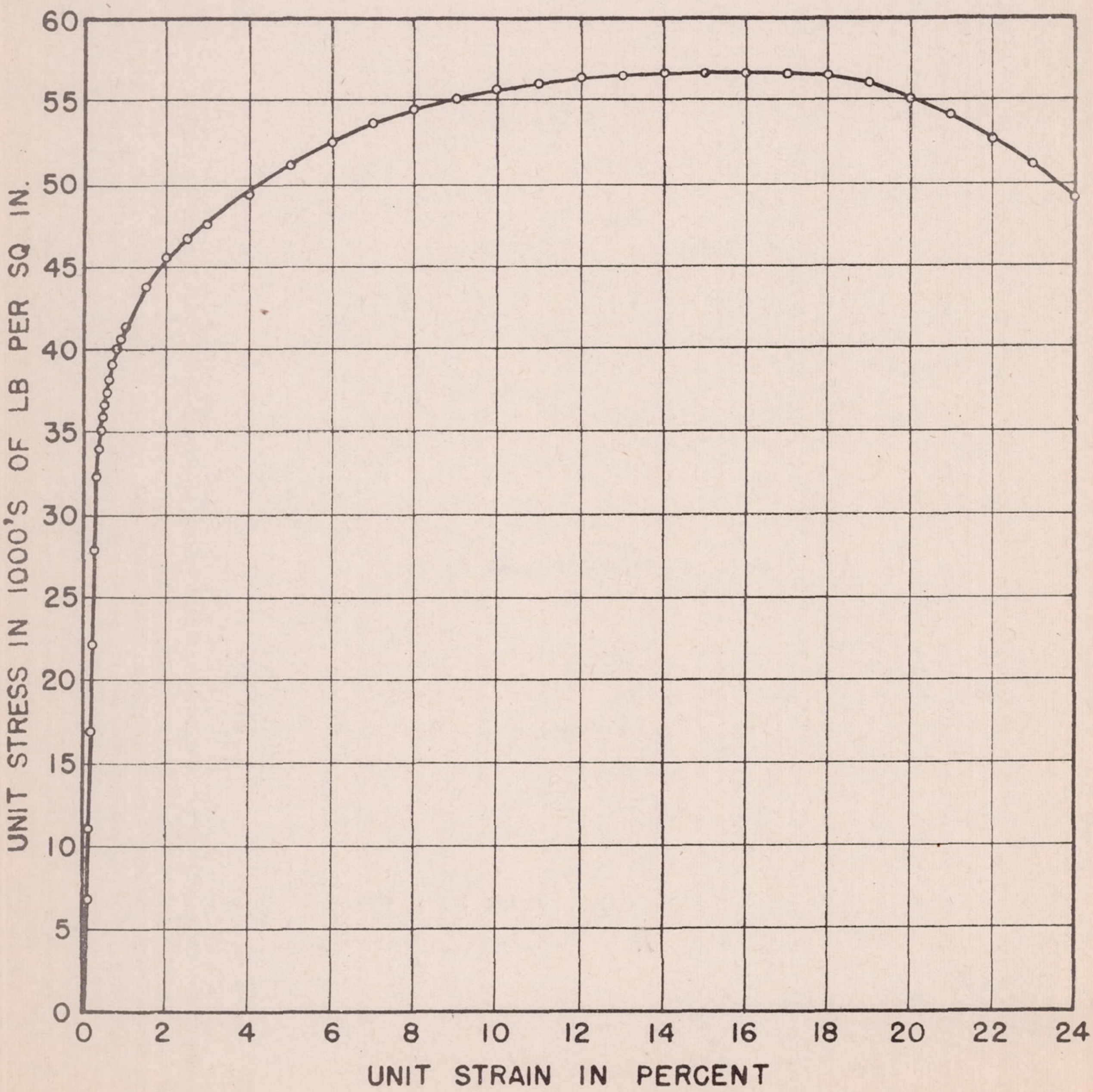


FIG. 10
STATIC TENSILE TESTS OF NOTCHED SPECIMENS OF 25S-T ALLOY

LOWER PORTIONS OF STRESS-STRAIN DIAGRAMS

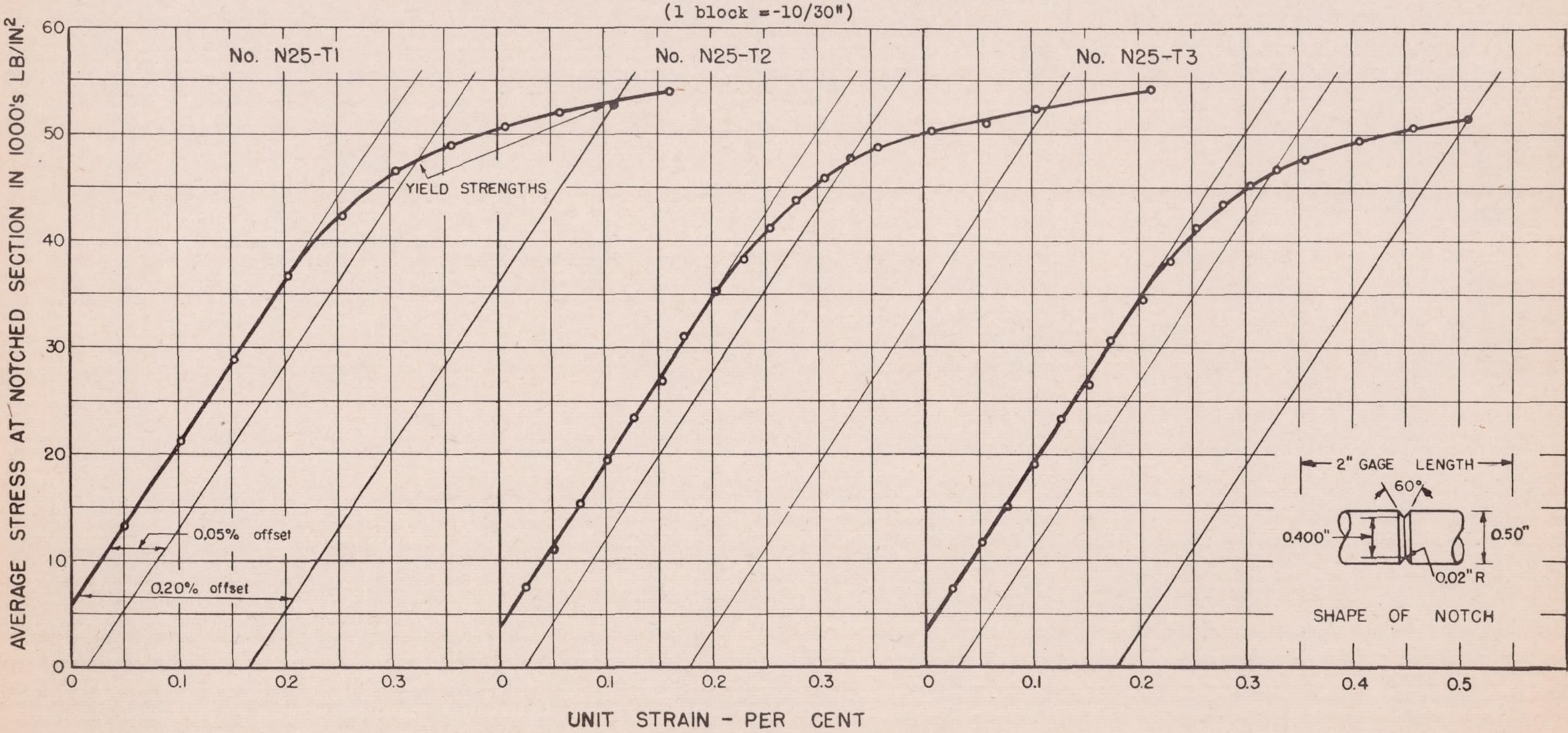


FIG. 11

STATIC TORSION TESTS — 25S-T ALLOY

SPECIMENS: 2 IN. GAGE LENGTH; 0.56 IN. DIAMETER

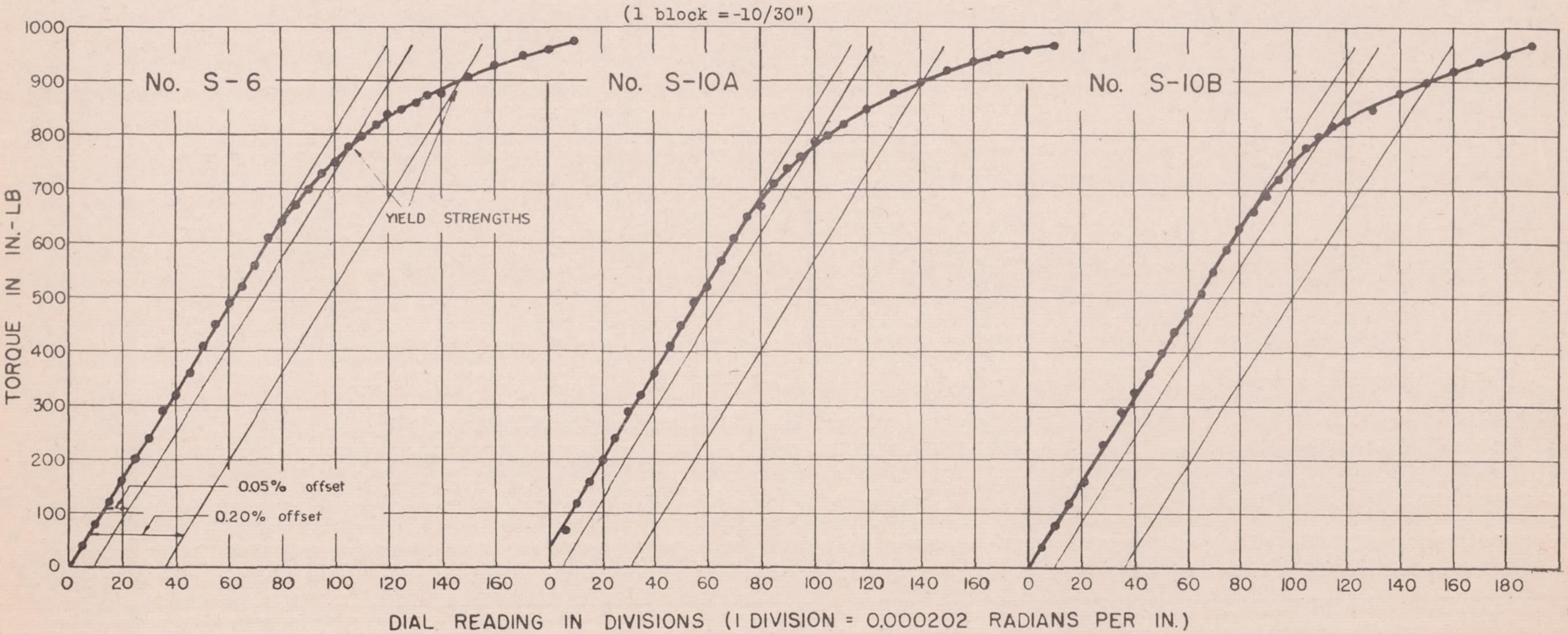


FIG. 12

RESULTS OF TENSION AND BENDING IMPACT TESTS

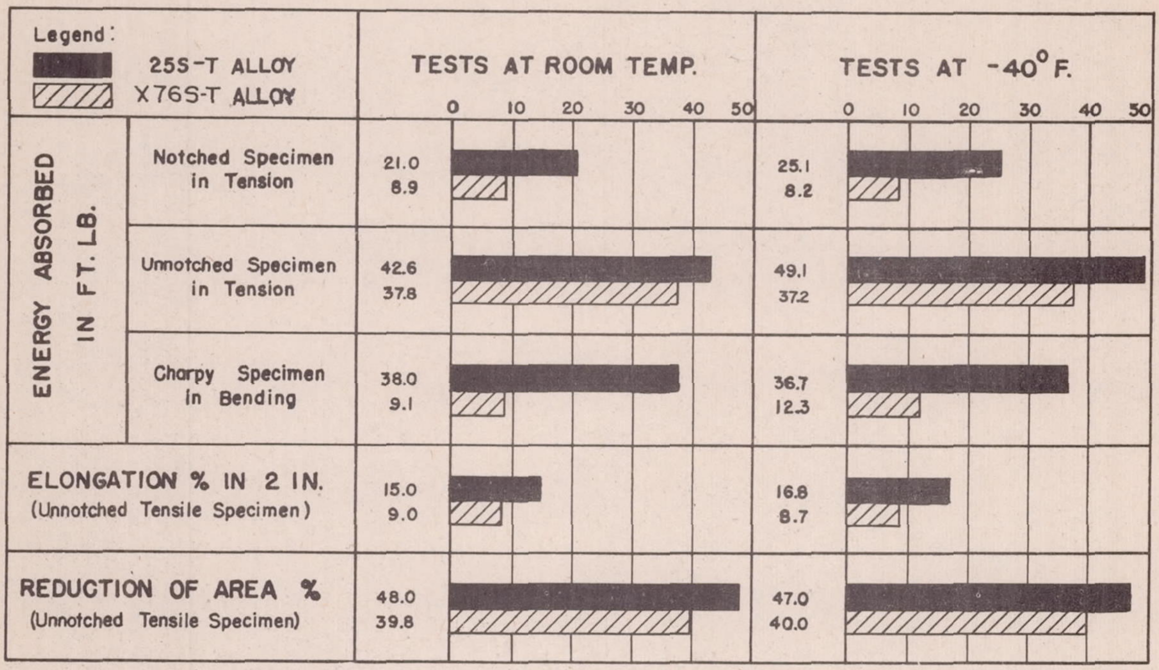


FIG. 13

ROTATING BEAM FATIGUE TESTS OF 25S-T ALLOY

Using Krouse Machine at 6000 rpm

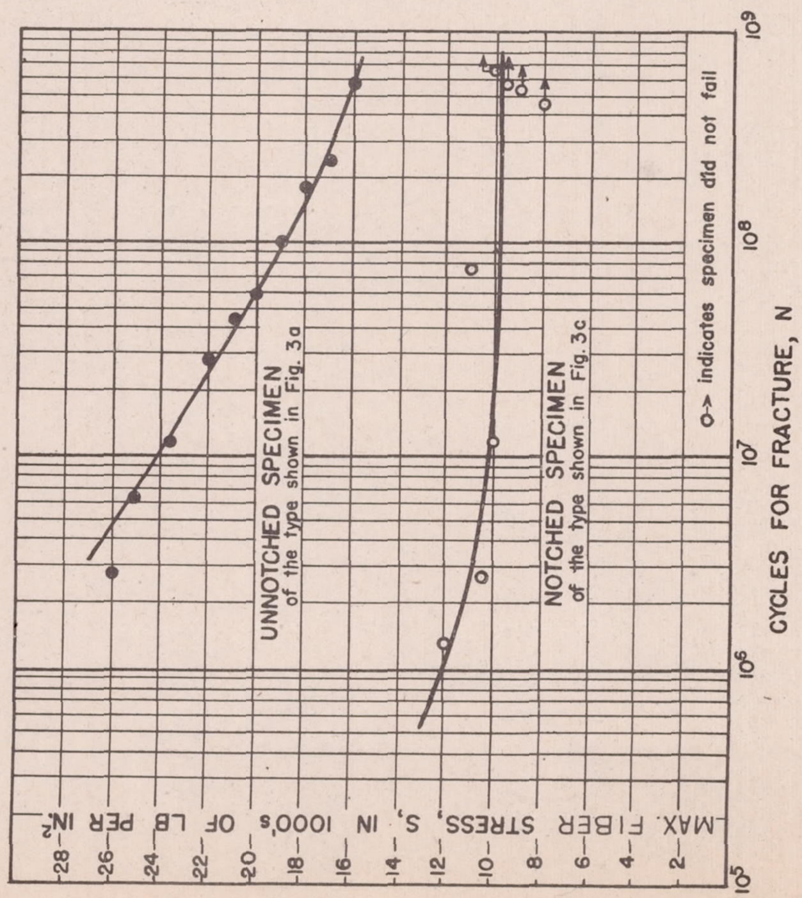


FIG. 14
ROTATING BEAM FATIGUE TESTS
OF 25S - T ALLOY

Using Small High-Speed Machines At 10,000 rpm

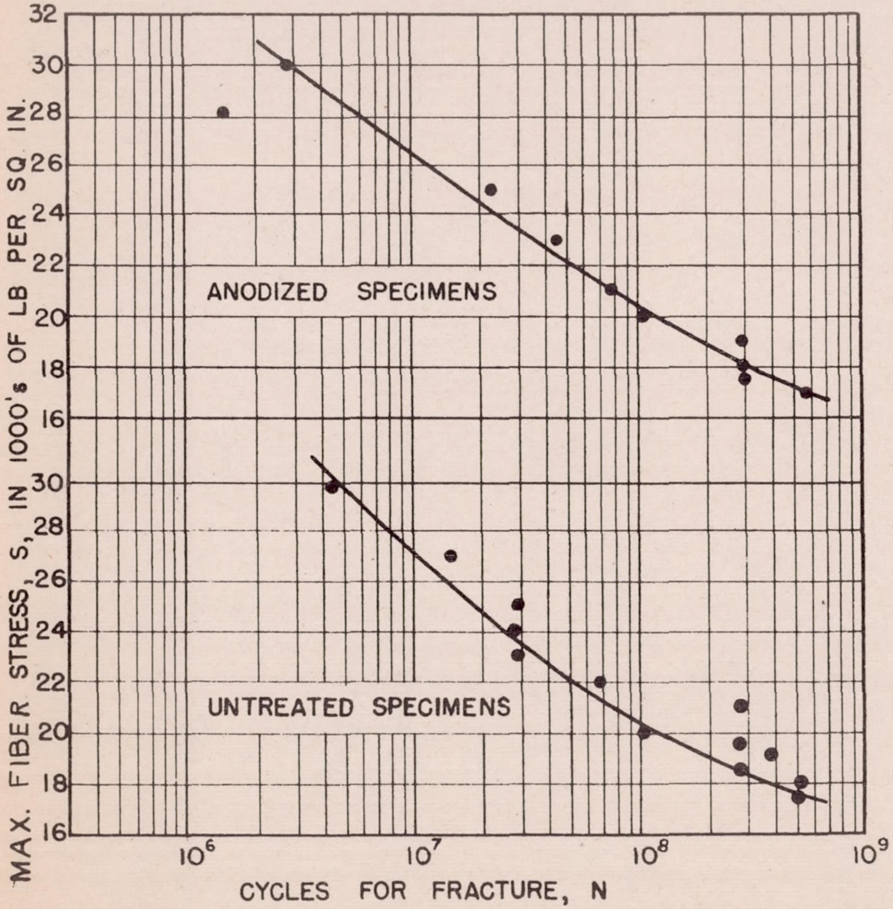


FIG. 15
VIBRATORY BENDING FATIGUE TESTS
OF 25S - T ALLOY

Completely Reversed Stress Cycle

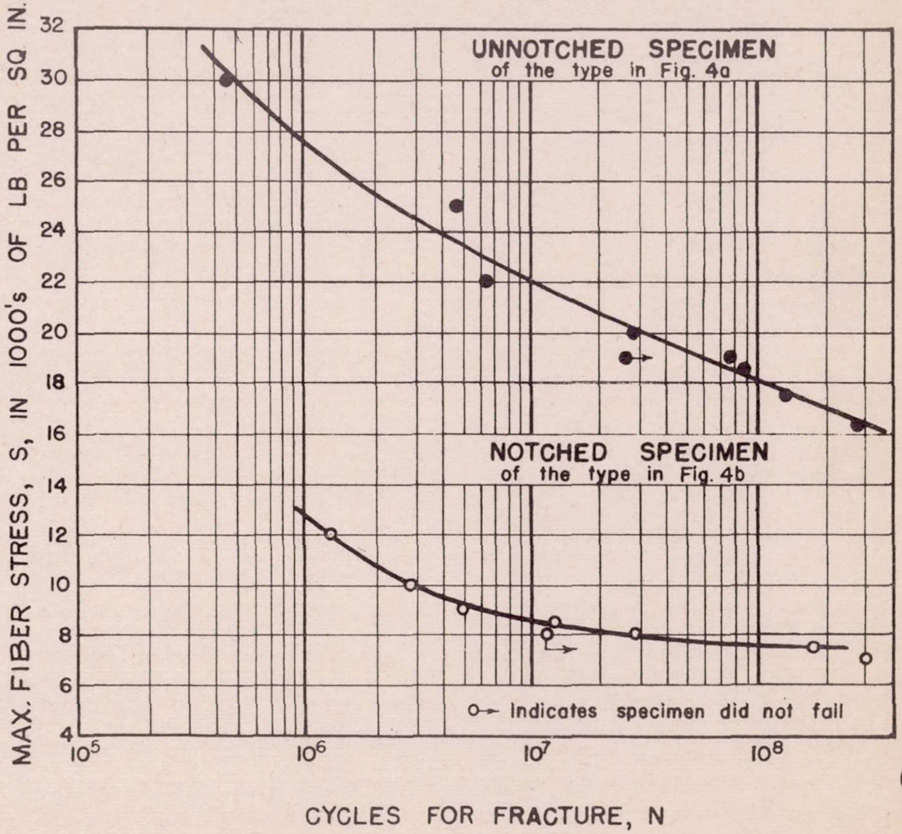
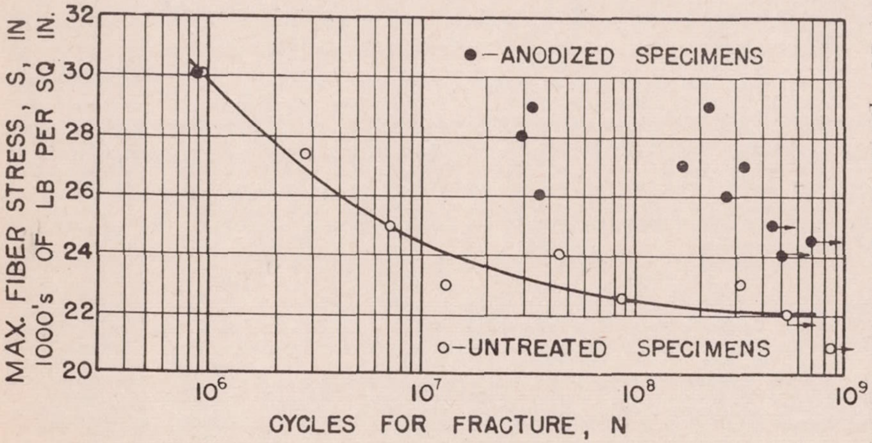


FIG. 16

ROTATING BEAM FATIGUE TESTS OF X76S-T ALLOY

Using Small High-Speed Machines At 10,000 RPM



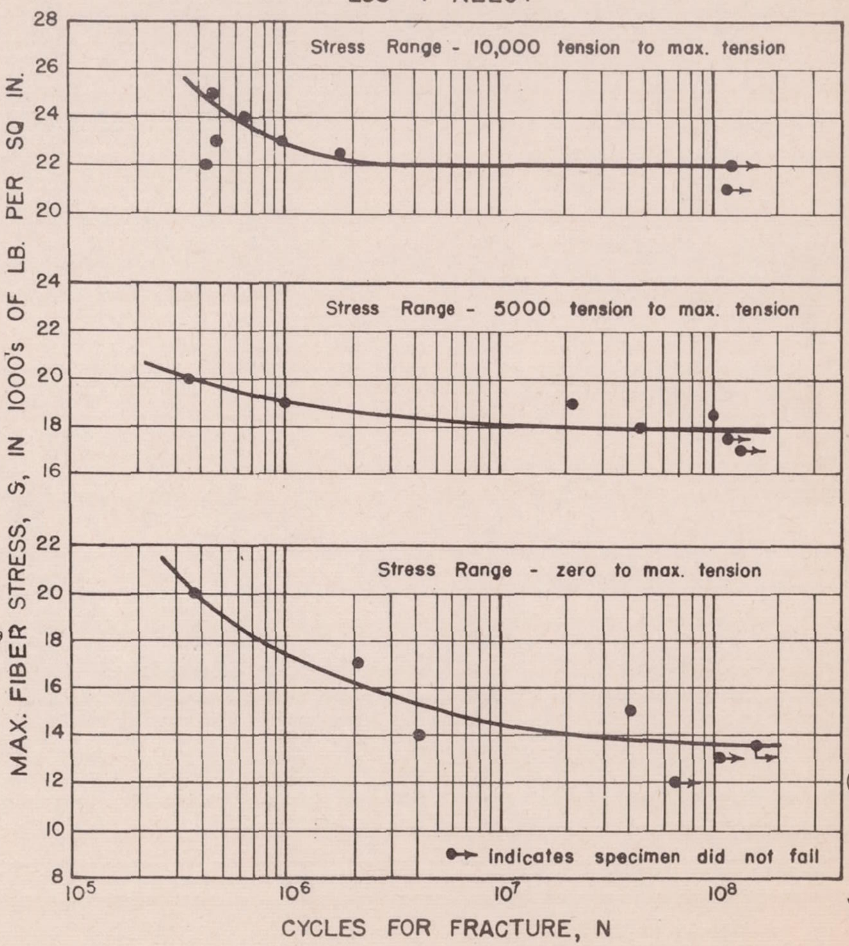
—• indicates specimen did not fail

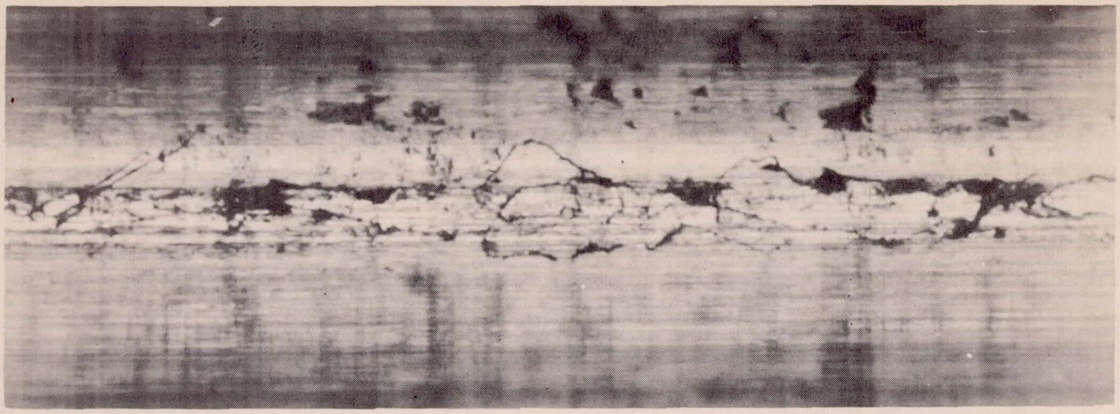
FIG. 17

VIBRATORY BENDING FATIGUE TESTS OF NOTCHED SPECIMENS

Specimens of type shown In Fig. 4b.

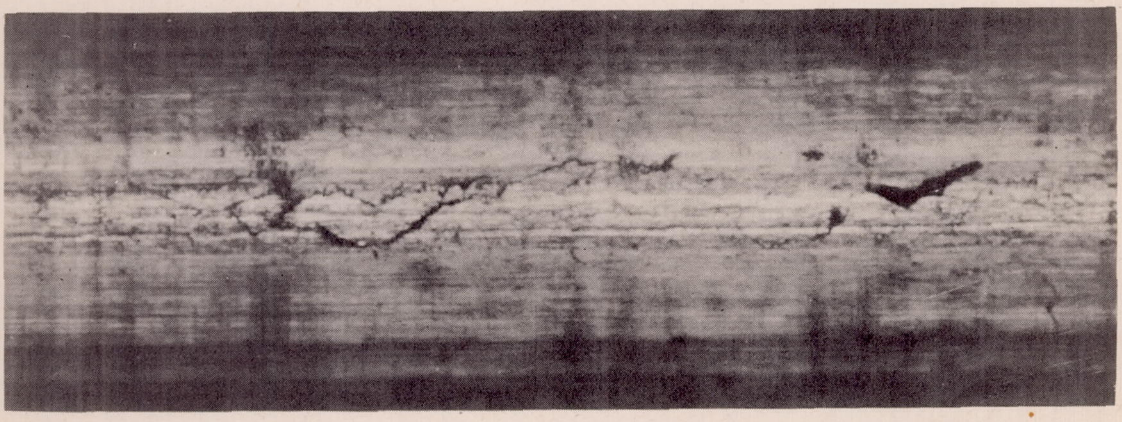
25S-T ALLOY





(a) After 18 million cycles of stress; range from +4000 to -16000 lb/sq in.

(b) After 36 million cycles of stress; range from +4000 to -14000 lb/sq in.



(c) After 64 million cycles of stress; range from 0 to -17500 lb/sq in.

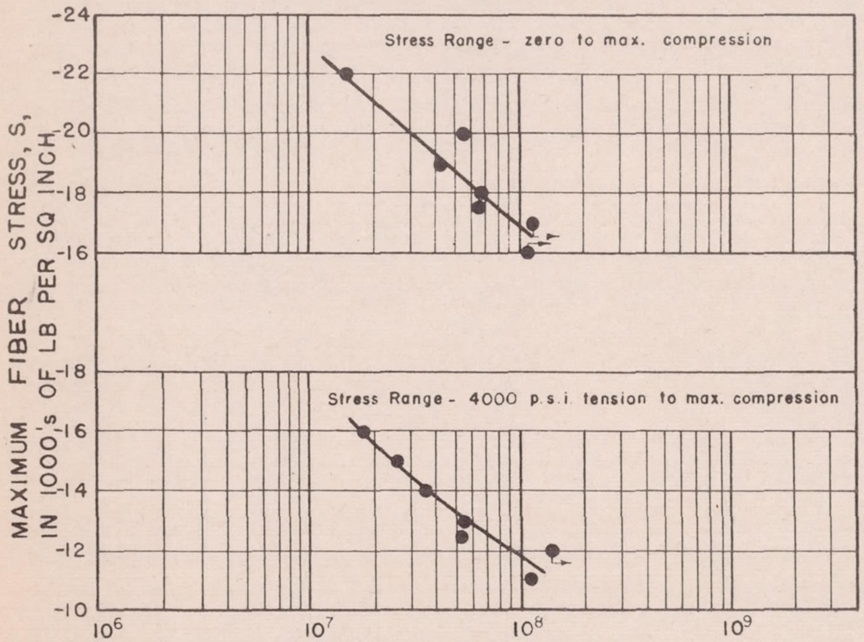
Figure 18.- Cracks formed at root of notch in specimens of 25S-T alloy tested in compressive stress cycles.

FIG. 19

VIBRATORY BENDING FATIGUE TESTS OF NOTCHED SPECIMENS

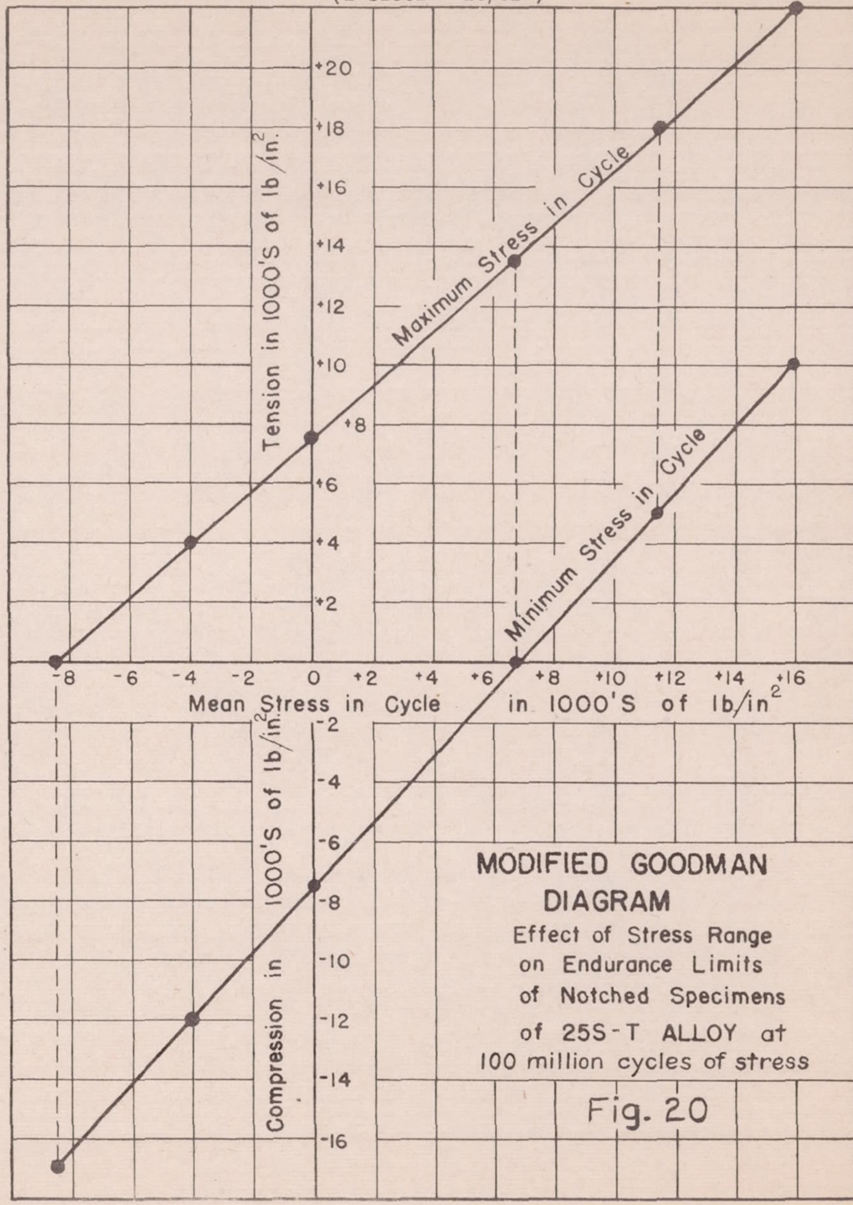
Specimens of type shown in Fig. 4b.

25S-T ALLOY



indicates specimen did not fail

(1 block = 10/32")



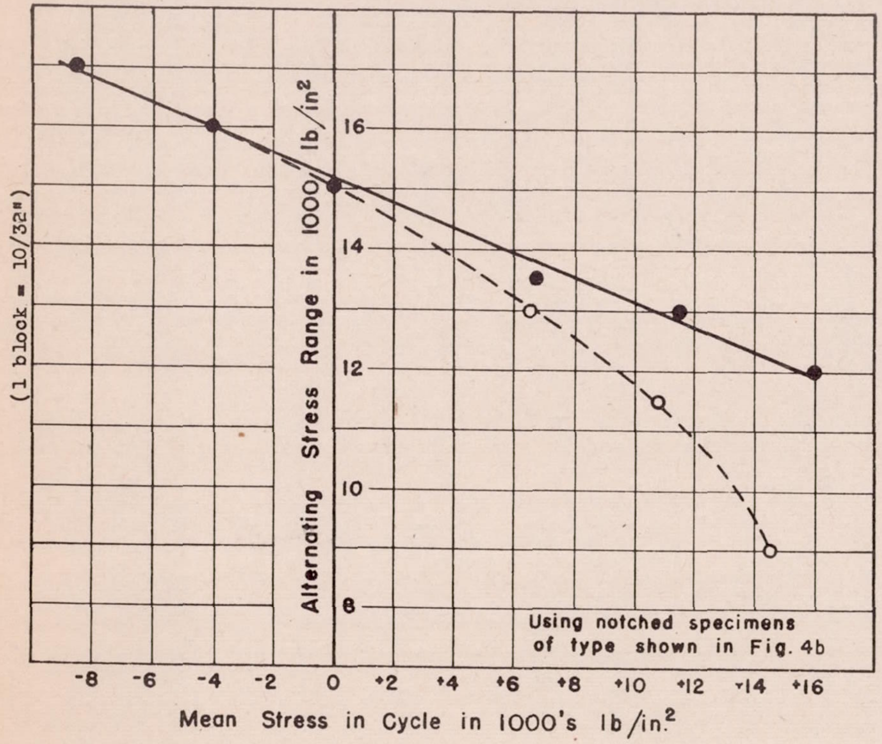
MODIFIED GOODMAN DIAGRAM

Effect of Stress Range on Endurance Limits of Notched Specimens of 25S-T ALLOY at 100 million cycles of stress

Fig. 20

FIG. 21

EFFECT OF MEAN STRESS ON MAX. SAFE ALTERNATING STRESS RANGE FOR 100 MILLION CYCLES.



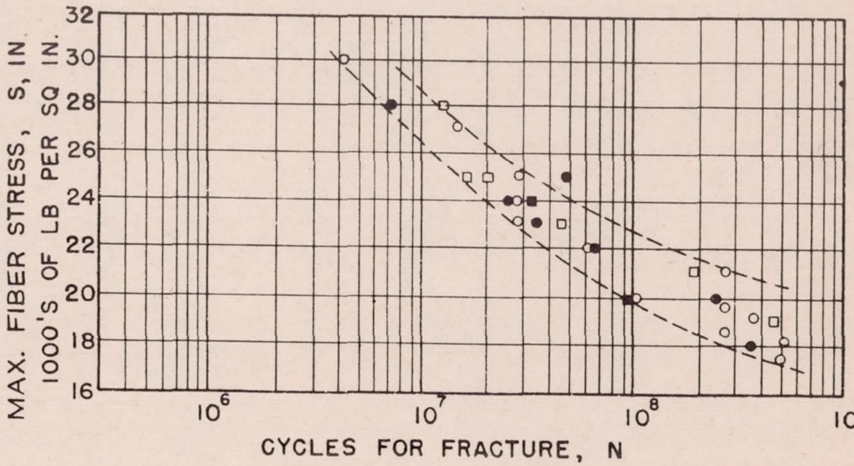
Legend:
●—● 25S-T ALLOY
O--O X76S-T ALLOY

FIG. 22

EFFECT OF PRESTRESSING ON FATIGUE STRENGTH OF 25S-T ALLOY

Specimen 3-b tested in

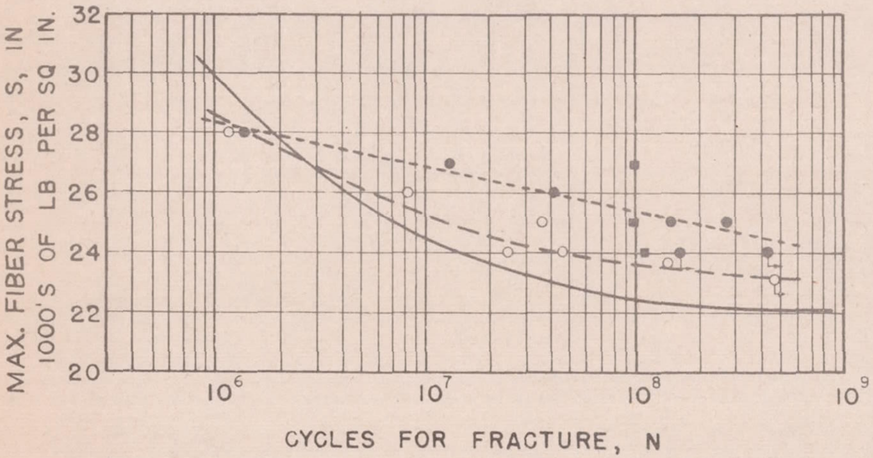
Small High-Speed Machines At 10,000 RPM



Legend:
■ Specimens prestressed at 15,000 p.s.i. for 100 million cycles before testing
□ Specimens prestressed at 16,500 p.s.i. for 100 million cycles before testing
● Specimens prestressed at 18,500 p.s.i. for 100 million cycles before testing
o Test of 25S-T without prestressing
--- Scatter band for 25S-T with no prestressing

FIG. 23
EFFECT OF PRESTRESSING ON FATIGUE STRENGTH OF X76S-T ALLOY

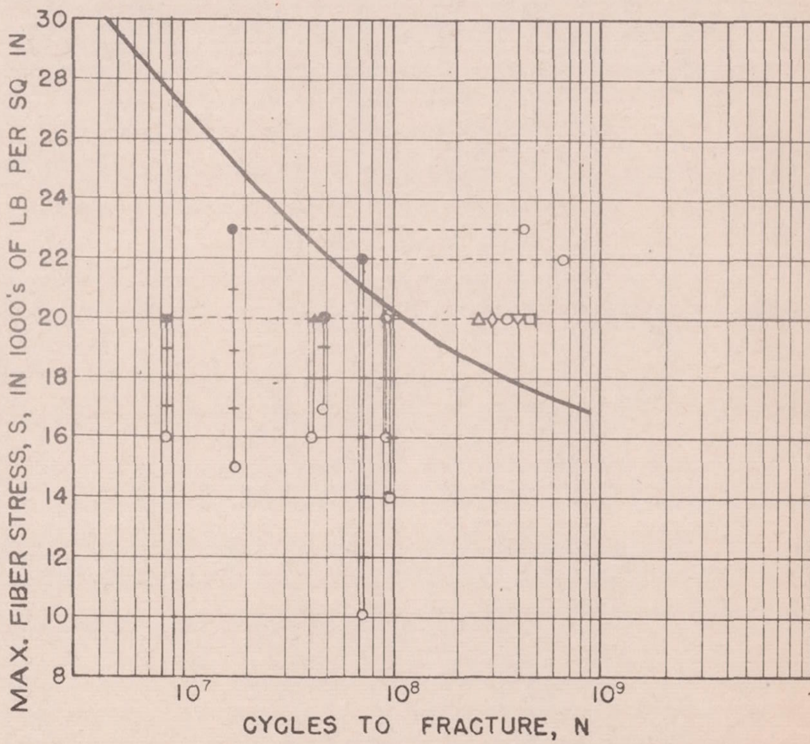
Specimen 3b tested in
Small High-Speed Machines At 10,000 R P M



Legend:
- ■ Specimens prestressed at 19,000 p s i for 100 million cycles before testing
- ○ Specimens prestressed at 21,000 p s i for 100 million cycles before testing
- ● Specimens prestressed at 20,000 p s i for 100 million cycles before testing
- —— Normal S-N curve for X76S-T Alloy, taken from figure 16.
- ⟶ Indicates specimen did not fail

FIG. 24
UNDERSTRESSING STEP-UP TESTS OF 25S-T ALLOY

Specimen 3-b



Normal S-N curve for 25S-T Alloy, taken from figure 14.